Greening the Internet with Content-Centric Networking

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ABSTRACT

Our energy efficiency analysis of various content dissemination strategies reveals that a change in network architecture from host-oriented to content-centric networking (CCN) can open new possibilities for energy-efficient content dissemination. In this paper, we consider energy-efficient CCN architecture and validate its energy efficiency via trace-based simulations. The results confirm that CCN is more energy efficient than conventional CDNs and P2P networks, even under incremental deployment of CCN-enabled routers.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design

General Terms

Design, Performance

1. INTRODUCTION

The vast majority of current Internet usage consists of content being disseminated from a source to a number of users, ranging from distributing conventional multi-media data (e.g., IPTV, Hulu and Netflix) to sharing user generated data over the web such as text, image, and video data (e.g., Facebook, Twitter, and YouTube). To meet growing demands service providers like Google, Yahoo, and Microsoft are ushered to invest in large data centers with hundreds of thousands machines distributed across different geographic regions.

Due to the sheer size, data centers consume significant energy – the U.S. Environmental Protection Agency (EPA) estimates that servers and data centers could consume 100 billion kilowatt hours at a cost of $7.4 billion per year by 2011 [8]. A number of different approaches have been proposed to address this problem; e.g., introducing efficient cooling methods, dynamically provisioning servers to account for diurnal usage patterns [7], and scaling power consumption of servers proportional to their utilization (also known as energy-proportional computing) [4, 13].

Along with the expansion of data centers, backbone network providers have been increasing network capacity to meet the demands, by deploying a large number of high-speed routers and fiber cables; and large service providers also build their own private networks for more efficient content delivery [9]. The Internet has been rapidly growing [5] and is now a web of tens of millions of networking devices consuming considerable energy (comparable to servers in case of routers), which could be always as high as the maximum nameplate [1] regardless of utilization [6].

Both industry and academia have been striving to improve energy efficiency of networking devices and eventually to realize so called *energy-proportional networking*: i.e., the energy consumption is proportional to utilization of network interfaces. Thus far, several techniques have been proposed toward this goal [3, 14]; e.g., dynamic voltage and frequency scaling (DVFS) of line cards and putting them in sleep mode during idle time, and coordination of intermediate routers for batch processing to elongate idle durations (à la Wake-on LAN).

The capability of energy-proportional computing and networking could save considerable amount of energy for Internet-scale content dissemination. Yet as user demand grows, the overall traffic increases, and so does the energy consumption. It is even postulated that demand growth may outpace transport capability, causing the sky falling of the Internet. This is partly true because optical networking is rapidly approaching the Shannon capacity limit, and tradeoffs between spectral efficiency and sensitivity make capacity improvements very difficult [17].

One possible method of alleviating this problem is to push content to the network edge as in content distribution networks (CDNs) such as Akamai and Limelight, so that we can significantly reduce transit traffic in the network backbone, thereby saving energy used for data transport. An extreme case to this end would be a nano data center (NaDa) where an ISP coordinates nano servers in users' home gateways to distribute content in a peer-to-peer (P2P) fashion, which can potentially reduce the transit traffic [16]. However, networking devices have a wide spectrum of energy consumption for packet forwarding (joules per bit), and surprisingly, it rapidly goes up as packets travel toward end users. For instance, when delivering the same amount of data, home gateways and desktop PCs could consume 100 and 1000 times more energy than core routers, respectively. Thus, distributing content from these less energy-efficient machines may result in higher energy consumption even with

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[1] The nameplate power is a device's hardware limit for maximum power draw.

minimal transit traffic across networks.

In this paper, we show that a change in network architecture opens new possibilities for energy-efficient content dissemination. *Content-centric networking* replaces host-to-host conversations with named data oriented communications [11, 12, 10] by introducing content routers into the network. While the basic operation of a content router is very similar to that of an IP router, the key departure is that it supports name-based routing and caching for content retrieval throughout the network. This way, content-centric networking obviates the need of deploying pre-planned, application specific mechanisms such as CDNs and P2P networks, which require sophisticated network services for mapping named content to hosts.

Beyond fast, reliable access to content, we advocate the use of content-centric networking for the sake of energy-efficient content dissemination and make the following contributions.

- We present an energy-efficient content router architecture, ranging from core routers to home gateways. By comparing different content distribution platforms, we show that energy-proportional computing and networking features should be incorporated in content-centric networking design. Furthermore, we show that power consumption of content router components such as memory and disks must be considered when configuring energy-efficient content routers.

- We validate the energy efficiency of content-centric networking via a trace-based simulations using a *traceroute* data set. By considering various incremental deployment scenarios (both core and edge), we show that content-centric networking outperforms conventional CDNs and P2P networks under the considered scenarios.

2. ENERGY EFFICIENT CONTENT DISSEMINATION

2.1 Content dissemination methods

A content distribution network (CDN) maintains content servers located in multiple sites such as backbones and ISP points-of-presence (PoP). When a user makes a request, the CDN chooses a server so as to improve user-perceived performance in terms of delay and throughput. The current design of CDNs can be differentiated based on where the content servers are located. One approach is to build large data centers at a few key locations connected using private high speed links [9]. This method is popular among large content service providers such as Google, Yahoo, Amazon, and Limelight. Another approach mainly used by Akamai is to deploy a large number of small content server clusters scattered across the Internet in multiple ISP PoPs and backbones. Since servers are highly distributed, locating a proper content server requires sophisticated algorithms such as real-time server monitoring and extensive network measurement, and the tasks of maintaining and managing the networks are very challenging.

The extreme case of a highly distributed approach is peer-to-peer (P2P) content distribution where content servers are located at the customer premises. This includes BitTorrent-like file swarming and nano data center (NaDa), a distributed content distribution platform based on nano servers in home gateways. In P2P content distribution, a tracker typically maintains a list of content servers to help peers locate one another. Moreover, content is divided into a number of small pieces, and peers cooperatively share whatever pieces they have. NaDa shares the same idea as BitTorrent with the key difference that an ISP manages and coordinates nano servers. Thus, NaDa does not suffer from free-riding, node churning, and lack of awareness of underlying network conditions.

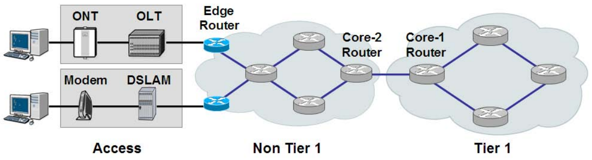

Figure 1: Internet topology.

2.2 Energy efficiency comparison

Delivering content from servers to end users involves various networking devices in between. We survey energy efficiency of network devices with an underlying assumption of energy-proportional computing and networking. We consider backbone routers, edge routers, and access network devices such as digital subscriber line (DSL) and gigabit passive optical network (GPON), and capture energy efficiency by Watts per Gbps, or W/Gbps (i.e., amount of energy for forwarding gigabit data).

For the backbone, we consider one of Cisco CRS 1 series router with 8 slots in a single shelf. There are 8 line cards each of which supports 40 Gbps of data forwarding. The maximum forwarding rate is 320 Gbps, and its peak power consumption is 4834 W. CRS 1's energy efficiency is 15 W/Gbps. A less powerful backbone router Cisco GRS 12000 has 7 line card slots and supports rate up to 27 Gbps at the peak power consumption of 800 W [6]. GRS's energy efficiency is 28.6 W/Gbps. Cisco 7507, an edge router supports 5 line cards and supports forwarding rate up to 5 Gbps at the peak power consumption of 400 W. The 7507's energy efficiency is 80 W/Gbps. Edge routers tend to spend more energy than core routers.

Both DSL and GPON need multiplexing machines at the service provider's central office, which are called digital subscriber line access multiplexer (DSLAM) and Optical Line Terminal (OLT), respectively. Moreover, users access networks via home gateways such as DSL modem for DSL and optical network terminal (ONT) for GPON. For a DSLAM, we consider Zyxel IES-500M, which has 10 slots supporting 48 ADSL ports. Assuming a maximum speed of 10 Mbps per line, the aggregated rate is 3.85 Gbps at a peak power consumption of 800 W, and IES-500M's energy efficiency is 208.3 W/Gbps. A typical DSL modem (e.g., D-Link DSL 2320B) consumes round 15 W, and its energy efficiency is 1536 W/Gbps. Unlike DSLAM, GPON's OLT can deliver a much higher aggregated rate. Fujitsu FA2232U has 16 fiber slots each of which accommodates 32 subscribers (50 Mbps per user) at the peak power of 400W, and its energy efficiency is 16 W/Gbps. Due to the sheer aggregated traffic volume, ISPs (e.g., Verizon) connect an OLT directly to collector rings, an edge optical network with reconfigurable optical add/drop multiplexers (ROADMs). The efficiency of a GPON gateway is much better than a DSL modem. For instance, Allied Data's GPON Gateway consumes 12 W at the speed of 50 Mbps, and its energy efficiency is 245.8 W/Gbps.

Content servers could be blade servers in a data center, home PCs, and nano servers in home gateways. Note that while blade servers in a data center could fully utilize its

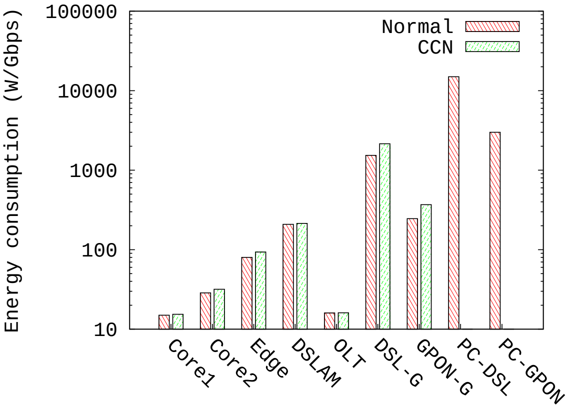

Figure 2: Energy consumption of networking devices

maximum server throughput (under no oversubscription scenarios), both home PCs and nano servers are limited by their uplink rates (<50 Mbps). A blade server with Xeon processors has an energy efficiency of 360W/Gbps [16], which is comparable to that of a nano server in a GPON gateway (245.8 W/Gbps). A typical PC with a dual core processor spends around 150 W when used for P2P file sharing [1], and the access connection has an energy efficiency of 15KW/Gbps and 3KW/Gbps for DSL and GPON, respectively

The energy efficiency of networking devices is visualized in Figure 2. From our analysis, we conclude that (1) core routers have better energy efficiency than edge routers; (2) optical access networks are much more energy efficient than legacy access networks such as DSL; and (3) nano servers in home gateways (with GPON) have energy efficiency comparable to content servers in the data centers, yet they are an order of magnitude more energy efficient than PC-based servers.

2.3 Toward content-centric networking

Our analysis shows that content servers (in data centers or in users' premises) are an order of magnitude less energy efficient than networking devices such as core/edge routers and optical multiplexers. This observation indicates that today's host-to-host based content distribution is inherently less energy efficient and brings home to us the value of exploiting the capability of energy-efficient networking devices using a radically different approach, namely content-centric/oriented networking where queries and data are routed based on content name which can be either opaque or structured (as in URL). In recent years, a number of different approaches have been proposed in the literature such as Data-Oriented Network Architecture (DONA) [12], TRIAD [10], and Content Centric Networking (CCN) [11]. Among these proposals, this paper focuses on CCN proposed by Jacobson et al. [11] because it provides an ideal platform for network-wide content caching.

CCN uses user-friendly, hierarchical names like URL. As in BitTorrent-like file swarming, the original content is divided into multiple chunks. In CCN, the content publisher signs each chunk along with its name to guarantee secure linkage between name and content chunk (i.e., a standard digital signature of name+content); intermediate routers can validate an incoming chunk using this per-chunk signature. A content publisher announces content availability à la BGP prefix announcement. The basic operation of a CCN router is very similar to an IP router. An interest (or request) packet arrives on an interface, and then a longest-match look-up is done on *its name* to make a forwarding decision. If there are multiple servers announcing content availability, an interest packet is forwarded toward all these content sources. CCN routers support caching within the network. Any intermediate CCN routers on paths that have the requested chunk can answer the request. Note that per-chunk signature is a key enabler for CCN's content-caching capabilities. The request chunk is then delivered by following a reverse path created while forwarding the interest packet. Since a large fraction of the current Internet traffic is redundant [2], this technique could significantly reduce redundant content transmissions in the network.

Given this, we investigate how to build energy-efficient CCN routers. The critical components are storage devices, namely DRAM, Solid State Drives (SSDs), and Disks. Modern routers have a dedicated forwarding engine for each line card, a routing processor for control packets (e.g., routing, network management), and a set of switching fabrics that interconnect pairs of arbitrary interfaces. Forwarding engines can communicate with the route processor via a high speed backplane. DRAM and disks are power-hungry (e.g., 2.5 W/GB for DRAM, and 12W per disk) compared to SSD (e.g., 1 W for 32 GB SSD) [13]. Thus, it is desirable to implement a hierarchical storage structure spanning both forwarding engines and the route processor: i.e., forwarding engine can be equipped with additional DRAM and SSD (say, 4 GB of DRAM and 32 GB of SSD), and the route processor can have a large storage device (say, Terabytes of disk space). If a router has 8 line cards, for example, this configuration incurs additional power usage of 100 W. As we will see, this extra overhead is reasonable in most network devices except the home gateways. In NaDa, we should only install small amount of DRAM and SSD (say, 2 GB DRAM and 32 GB SSD) due to the energy efficiency concern. Note that when a user does not publish any data, CCN capability in gateways can be safely turned off to save energy. In Figure 2, we incorporate the abovementioned configurations into the energy consumption calculation of networking devices (considered in the previous subsection). The results show that CCN capability slightly increases energy consumption when comparing W/Gbps.

3. EVALUATION

To validate our claim, we use a traceroute data set in [15], which captures a single snapshot of the network of the top 20 content providers ranked by Alexa in Sept. 2007. It was collected by querying these providers from 18 different traceroute servers located in the US. We identify which of the hops in the traceroute path belongs to Tier-1 ISPs using a publically available Tier-1 ISP list. For the sake of analysis, we assume that Tier-1 ISPs use core routers, and the other nodes in a path are either smaller core or edge routers. We show the benefit of CCN under incremental deployment scenarios by varying the fraction of CCN-enabled core and edge routers from 0 to 100% with in increments of 20%. For a given traceroute path, we randomly select a given fraction of core and edge routers as CCN routers, respectively. We assume that users download popular content, and thus, any of the intermediate CCN routers can serve the content. We measure the total energy consumption for downloading 1 Gbits of content from these content service providers.

Path length analysis: We show that large content providers such as Yahoo and Google have content servers located in a few large data centers that are interconnected using private

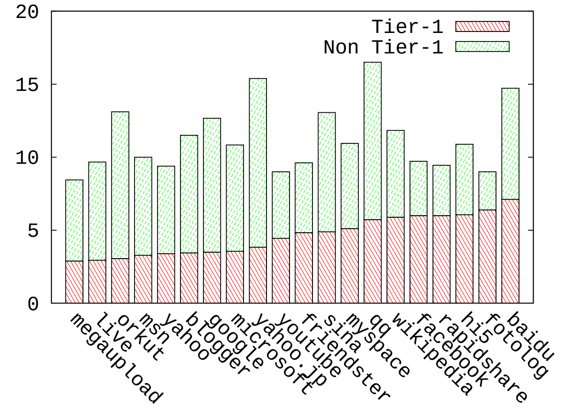

Figure 3: Traceroute path analysis: Tier 1 hops and Non Tier-1 hops

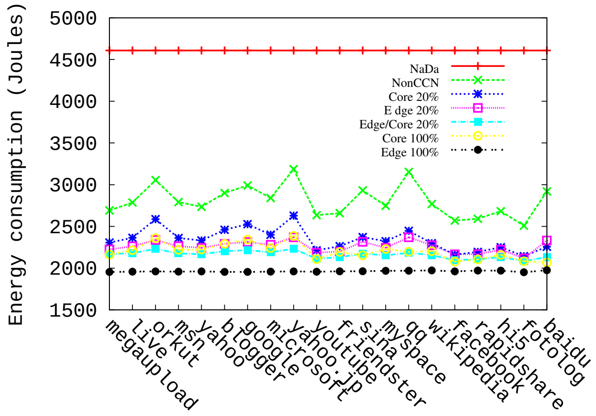

Figure 4: Energy consumption comparison

high speed networks. In Figure 3, we plot the average number of hops to reach those content providers and the average number of Tier-1 hops. As shown by Gill et al. [9], larger content providers such as Yahoo, Google, and Microsoft tend to bypass Tier-1 ISPs and directly connect to their private networks, thus, showing much smaller Tier-1 hop counts.

Energy consumption comparison: In Figure 4, we plot the energy consumption of different deployment scenarios of CCN nodes (20% and 100%) and compare its performance with the case without using CCN and NaDa. Even with 20% deployment of CCN routers in the cores, CCN can effectively reduce the hop length, thereby reducing energy consumption more than 15%. It is more effective to deploy CCN nodes at the edge. For instance, the scenario with 20% deployment in the edge routers performs almost as good as the scenario with 100% deployment in the core. A caveat of this result is that the total number of CCN routers will be much greater when deploying them in the edge, because the number of edge routers tends to grow exponentially. The figure also shows that NaDa's energy efficiency is even worse than non-CCN scenarios. NaDa uses power-hungry nano servers twice since content is disseminated from one nano server to the other.

4. CONCLUSION

We showed that networking devices ranging from core routers to home gateways have a wide spectrum of energy efficiency, and content servers (in data centers and in end users' premises) are an order of magnitude less energy efficient than core and edge routers. Given that today's host-to-host based content distribution is inherently less energy efficient, we used a radically different approach, namely content-centric networking (CCN) to exploit the capability of energy-efficient networking devices. Our trace-based simulations showed that CCN is more energy efficient than conventional CDNs and P2P networks, even under incremental deployment of CCN-enabled routers.

There are several directions of future work. We assume *perfect* energy-proportional networking; i.e., there is no energy loss during idle time. In practice, however, we expect a certain amount of energy loss (e.g., 10% of peak power) even with *near* energy-proportional networking. CCN should be able to perform energy-aware routing and traffic consolidation such that it can increase energy efficiency of CCN routers. In some cases, CCN routers should be able to dynamically turn on/off CCN capability for energy conservation, which requires a careful investigation of CCN layers.

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